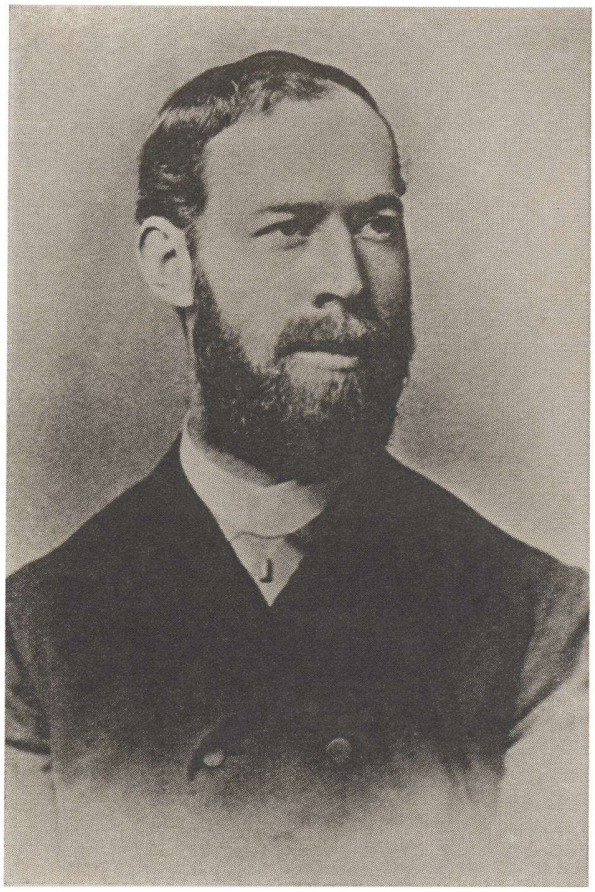
The early history of electronics

II. The experiments of Hertz



The epoch-making discoveries of Hertz during 1887–1888, on which the development of practical radiotelegraphy was based, are described in this second installment of our continuing series on the rise of electronics as a branch of technology

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In the first article in this series, we saw how experimental proof that electromagnetic perturbations propagate as waves remained lacking even after FitzGerald suggested a way of designing a crucial experiment in 1883.[1] Over the years that followed, some further theoretical developments pertaining to the radiation of electromagnetic energy took place. The most notable advance was made by John Henry Poynting (1852–1914), who showed that the transport of electrical energy (until then associated with the flow of electric current in a conductor, by analogy with hydraulics) could be more generally expressed in terms of the electric and magnetic fields in the medium outside the wire.[2]

An attempt to advance the theory was also made by Hertz.[3] Half a century earlier, after Oersted had discovered that an electric current could produce a magnetic field, Ampère concluded that two current-carrying circuits should therefore exert forces on each other; in other words, they should be indistinguishable from real magnets. By analogy, argued Hertz, if a changing magnetic field could produce an electric force, such a force should be identical with the force arising from electrostatic charges. Two coils in which currents were changing should therefore exert electrostatic forces on each other.

This conclusion, which could not be obtained from the older electrodynamics, followed from Maxwell's equations and was shown to be wholly compatible with them; but that did not constitute a proof.

In 1879, the Prussian Academy of Sciences had set a competition calling for an experimental demonstration of any effect that dielectrics could be shown to have on electromagnetic processes. Helmholtz would have liked to see Hertz—who was his star pupil—devote himself to this question, and even offered him all the resources of his own institute for this purpose. Hertz rightly estimated that the effect sought was too small to be observed and decided to work on other problems instead, outside the field of electrodynamics altogether. But his interest in electrical oscillations dated back to his assistantship in Berlin. When he returned to electrical experimentation upon getting a professorial appointment and his own research institute in Karlsruhe a few years later, he was by no means a newcomer to the problem of electromagnetic radiation.

His first observation was made by chance. A piece of wire, formed into a loop that did not quite close, lay near a coil that was being used to discharge a Leyden jar. When the wire loop was in contact with any part of the coil, a small spark was seen to pass across the gap at each discharge. Here was evidence that electric waves were being propagated along the lead from the coil to the loop and reached one end of the loop before the other, so that

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Heinrich Rudolf Hertz (1857–1894) was born in Hamburg, where he received a combined classical and vocational education. He began to study engineering, but soon switched to physics and mathematics. In 1880 he received the doctorate *magna cum laude* in Berlin, where he had studied under the great Herrman von Helmholtz (1812–1894) and had also come in contact with Gustav Kirchhoff (1824–1887) and Eugen Goldstein (1850–1930). He served as assistant to Helmholtz for three years and then became *Privatdozent* at the University of Kiel, where he continued with his interest in Maxwell's electromagnetic theory. In 1885 Hertz was appointed professor of physics at the Technische Hochschule in Karlsruhe; it was here that the discoveries that made him famous were made. In 1889 Hertz succeeded Rudolf Julius Emanuel Clausius (1822–1888) as professor of physics at the University of Bonn, and he died there on January 1, 1894, a few weeks before his 37th birthday. Germany led the world in adopting his name for the unit of frequency; during the 1930s, the Nazis attempted to abolish this nomenclature (Hertz was half Jewish—40 years after his death, his widow and two daughters felt obliged to emigrate to Britain) but their ascendancy ended before the change could be implemented and the designation is now in international usage.

There is no book-length biography of Hertz. There is a short booklet by J. Zenneck, published by Verein deutscher Ingenieure in Berlin in 1929, and a lengthy entry by Max von Laue (1879–1960) in a book of biographies (Ref. 14). Shortly after Hertz's death, his daughter published a book of personal reminiscences and correspondence. Hertz's papers were edited by his pupil Philipp Eduard Anton Lenard (1862–1947) and published as *Gesammelte Werke* by Ambrosius Barth in Leipzig in 1895 in three volumes: (1) *Schriften vermischten Inhalts*, (2) *Untersuchungen über die Ausbreitung der elektrischen Kraft*, and (3) *Die Prinzipien der Mechanik*. English translations were published by Macmillan in London as: (1) *Miscellaneous Papers* (1896, translated by D. E. Jones and G. A. Schott); (2) *Electric Waves* (1893, translated by D. E. Jones); and (3) *The Principles of Mechanics* (1899, translated by D. E. Jones and J. T. Walley). Hertz's influence on the development of mechanics was likewise profound.

a spark passed across the gap. Electricity propagated along the wire at a finite velocity.

Although Hertz did not know it at the time, he was not the first to investigate the transmission of electromagnetic waves along wires. In 1870, Wilhelm von Bezold (1837–1907) had observed that waves were reflected from an open-circuited transmission line and that the velocity was essentially independent of the wire material.[4] (Later, when Hertz learned of von Bezold's work, he was quick to give him full credit for priority.) Similar investigations were being made in England,[5] notably by Oliver Joseph Lodge (1851–1940), who afterwards never ceased pointing out that he had been barely nosed out in making the great discovery. But Hertz's discovery was a much greater step forward. He found that a spark would pass across the gap of the coil or secondary circuit even when no connection at all was made to the discharge coil in the primary circuit.

At first, Hertz thought that the effect was much too irregular to be of use. On occasion the experiment depended on the observation of a spark no longer than 0.1 mm and so weak that it could be seen only after the eye had become adapted to a darkened room. But the fact remained that a method had been discovered for producing electrical oscillations and detecting them at a distance, so that the all-important tool for an experimental proof of Maxwell's theory was now available. A significant improvement was made when Hertz discovered that the effect became many times magnified when the size of the secondary circuit was adjusted so that its dimensions corresponded to the wavelength of the primary oscillations. Further elaborations were laid aside while Hertz sat down to describe his discovery.

In his paper, he reported the observed resonance effects and concluded, from the fact that the resonant response was not very sharp, that the oscillations were strongly damped.[6] He also noted that the secondary wire exhibited nodes at which no electrical effects could be observed.

Next, Hertz undertook a series of five investigations that, together with the initial announcement of his discovery, made him world famous. The first harked back to the competition of the Prussian Academy of Sciences and showed that the results were considerably affected when large dielectric bodies such as wood, sulfur, paraffin, or asphalt were interposed between the primary and secondary circuits.[7] This result confirmed one of the basic tenets of Maxwell's theory, that a dielectric body becomes polarized under the action of electromagnetic forces and becomes a source of electromagnetic effects itself.

In the second investigation Hertz went on to show that electromagnetic waves propagate with a finite velocity, moreover with a different velocity according to whether the propagation takes place through air or along a wire.[8] He sent waves along two such paths and looked for interference phenomena at the detector. He measured the velocity of propagation along the wire by calculating the frequency of the oscillations in the primary circuit and measuring the distance between nodes along the wire; the velocity is the product of frequency and wavelength. His results were in error. He obtained a ratio of about 3:2 between the two velocities, which made the velocity of propagation along the wires about two thirds

of the velocity of light.* Subsequent investigations by Ernst Lecher (1856–1926) showed that the two velocities were equal.[9]

The third investigation was concerned with the phenomena observed when the primary and secondary circuits were separated by a considerable distance.[10] The greatest distance conveniently available was the length of the lecture room, about 15 meters. The primary circuit was at one wall; the opposite wall was partially lined with a zinc sheet to form a reflector or mirror. By moving the secondary circuit between the two walls, Hertz found that the anticipated nodes and antinodes manifested themselves; the distance between nodes (half the wavelength) was about 4 meters. The creation of standing waves through interference between incident and reflected radiations was a definitive proof that electromagnetic radiation was of the same wavelike nature as light.

The next investigation was a theoretical one, an analysis of his radiator in the light of Maxwell's theory.[11] This radiator had in the meantime undergone several modifications. The primary circuit or *transmitter* had been replaced by a long wire that had a large metal sphere at each end and was interrupted at the center by a small gap. In a typical experiment, the wire was 1.5 meters long and the radius of each sphere was 15 cm. With this primitive apparatus Hertz was able to obtain the astonishingly high frequency of about 80 MHz. In the secondary circuit or *receiver*, the wire was bent into a loop and mounted on a wooden stand in such a way that the small gap between the ends could be adjusted by means of a micrometer and observed through a small telescope. This arrangement was a more sensitive one and experimentation could be carried on more reliably.

Although Hertz had shown that his results were compatible with Maxwell's theory and could not have been predicted on the basis of the older electrodynamics, the validity of which was therefore refuted, some uncertainties remained. The false result that the velocity of propagation along wires and in air differed was not predicted by Maxwell's theory. Another uncertainty arose when it was found, both by Hertz and by others who tried to repeat his experiments, that the position of the standing-wave nodes—and sometimes the distance between them—appeared to depend on the type of detector that was used. Both of these objectionable results were later found to be caused by experimental difficulties, largely connected with the size of the receiver and reflections from side walls. Nevertheless, for a time some doubt attached to the validity of all of Hertz's work. But no doubt at all remained after Hertz's final and most elaborate investigation, which was carried out toward the end of 1888.[12]

In that experiment, Hertz further modified the transmitter by omitting the metal spheres at the ends; instead, he made the wire much thicker and somewhat shorter. The frequency was thereby increased, and hence the wavelength decreased, to about 0.5 meter. The receiver now became a version of the older transmitter: a long wire interrupted by an adjustable gap. The size of the spark that could be produced in the receiver gave an approximate measure of the field strength.

*Hertz assumed that the positions of the maxima and minima were determined by the transmitter frequency. In his low-Q circuit, these positions depended on the *receiver* frequency instead, which varied from experiment to experiment.

Hertz now set about to prove that his waves behaved according to the laws of geometrical optics. He had already demonstrated one such property—simple reflection from a plane mirror. Now he located his transmitter along the focal line of a cylindrical reflector with a parabolic cross section, to concentrate the emanating waves into a narrow beam; and he improved the sensitivity of the receiver by placing it in a similar reflector. With this apparatus, he showed that the beam propagated rectilinearly and that it could be reflected from a mirror and refracted by a dielectric prism, in full accordance with geometrical optics. Since the dimensions of any apparatus used for such experiments must be large compared with the wavelength, he had to employ a prism about 1.5 meters high that was made of pitch and weighed over 100 kg. The results were not merely qualitative; he could show that the angle of refraction was very nearly that predicted from Maxwell's theory for a body with the dielectric constant of pitch. Finally, he showed that his waves exhibited polarization: their properties were different according to whether measurements were made in the plane of the transmitter or at right angles to it.

But Hertz himself was not entirely satisfied. In addition to showing that electromagnetic radiation exhibited the properties of light, he called on his colleagues to prove also the opposite contention, that light possessed electromagnetic properties.[13] "It strikes us as peculiar," writes one biographer, "even a little tragic, that he did not notice, or did not dare to acknowledge, that he had accomplished that proof himself. In enumerating the factors that tend to disturb his spark experiments, he repeatedly mentions irradiation by the light of another spark. This was the discovery of that photoelectric effect, as we should say today, whose cause was quite correctly connected by Wilhelm Hallwachs in 1888 in Leipzig with the fact that carriers of negative charge are liberated from the metal of the spark gap. The desired electrical effect of light is right there."[14]

The experiments of Hertz brought him quick recognition. The Royal Society invited him to London, where he renewed his acquaintance with some of the great British physicists and met others. He received offers of positions from all over the world, from America, from Berlin, from Bonn. He chose Bonn and moved there in the spring of 1889. The following year saw the completion of his great text on electrodynamics, *Untersuchungen uber die Ausbreitung der elektrischen Kraft*, published in Leipzig in 1892.[15] This work was translated into English by D. E. Jones as *Electric Waves*, a title suggested by Lord Kelvin.[16] The suggestion is sometimes made that Hertz's own title implies that he did not conceive of the propagation of electromagnetic energy as waves (*Ausbreitung* means "outspreading"); this is arrant nonsense. The book, a work of great clarity, went a long way toward correcting the faults of Maxwell's treatise and formed a model for all future textbooks of what now became the new electrodynamics. In this work, Hertz went beyond Maxwell; among other things, he considered the case of moving bodies and developed a theoretical basis for an important magnetic effect that had been observed by Wilhelm Conrad Röntgen (1845–1923) in 1888 as a result of the motion of a dielectric in an electric field. Incidentally, Röntgen's investigation also stemmed from the 1879 competition set by the Prussian Academy of Sciences.

Hertz devoted the remaining three years of his life to the theory of mechanics and did not return to electrical investigations—with one exception, an experimental investigation of the properties of cathode rays, about which we shall hear in a future installment.

Active development of radiotelegraphy began a few years after Hertz died in 1894, so that he had no direct part in it. But even during his lifetime, several engineers and scientists suggested that the new discovery might be used for communications. The very first suggestion was made in a letter to Hertz himself. This suggestion proved to be impractical and Hertz quite properly characterized it as such—an episode that has been sometimes cited to his discredit. That view is unjustified, as I have shown in detail elsewhere.[17]

What happened was that almost immediately after Hertz's results were published, an electrical engineer named Heinrich Huber from Munich, who was then working in the electric power station at The Hague in the Netherlands, wrote to Hertz to ask whether it would be possible according to his theory to transmit the invisible magnetic lines of force across a distance. (This letter, dated December 1, 1889, and the subsequent correspondence, are in the Deutsches Museum in Munich.) "In the first place," wrote Huber, "I have transformers and the telephone in mind." He enclosed a sketch showing the pole of an electromagnet in the focal point of a concave mirror and an induction coil in the focal point of a second mirror at some distance.

Hertz replied immediately, on December 3, pointing out that electromagnetic fields would produce propagating waves only if the fields were oscillating sufficiently fast. "But the oscillations of a transformer or a telephone are much too slow," he wrote. "Take a thousand oscillations per second, surely a high figure, yet the corresponding wavelength in the aether would be 300 kilometers, and the focal lengths of the mirrors employed would have to be of the same order of magnitude. If you could thus build a concave mirror as large as a continent, you might very well be able to set up the proposed experiments, but in practice nothing can be done; you would not perceive the slightest effect with ordinary convex mirrors. At least that is what I suppose."[17]

Various writers have taken this reply to signify that Hertz had no head for practical matters and conceivably even delayed the progress of radiotelegraphy for several years. This canard started when Karl Ferdinand Braun (1850–1918), the inventor of the cathode-ray oscillograph, stated incorrectly in an early text on radiotelegraphy that Hertz had been asked "whether his waves could not be employed for wireless telegraphy."[18] Another early account, published in London in 1904, says that Hertz "had not grasped the full significance of his own discovery"[19]; and the story is perpetuated in later writings.[14,20]

In fact, Huber had not mentioned radiotelegraphy at all and Hertz was neither technically inept nor responsible for delaying the invention of radiotelegraphy. In the first place, Hertz showed a remarkable mechanical aptitude from boyhood and in fact started to study engineering before he switched to physics. The advent of radiotelegraphy was unaffected by the correspondence, which was conducted in private, and more practical suggestions were not long in coming forth, as we shall see in the next article in this series. But above all, Hertz's reply was technically and scientifically flawless. The proposed method was adequate for neither radiotelephony nor power transmission. The method by which radiotelegraphy was brought into being, modulation and demodulation of a high-frequency signal, was a technical advance that came after Hertz's death and had not been mentioned by any contemporary.

The experiments of Hertz are an important milestone in the history of science, in that they provided an incontestible verification of Maxwell's work and thus dealt the *coup de grâce* to the theory of action at a distance. Their importance in the history of technology is scarcely smaller. Within a short time, they were followed by the development of radiotelegraphy and the beginnings of electronics as a significant branch of technology. We shall see in the next article in this series that the main obstacle between Hertz's experiments and the practical application of his results to radiotelegraphy was the lack of a more sensitive method of detecting the waves.

NOTES AND REFERENCES

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Correction. On page 95 of the first article in this series (see Ref. 1 above), the right-hand portrait is incorrectly identified as that of Sir Benjamin Thompson; it is, in fact, Silvanus Phillips Thompson.